Consideration of Inter-Pulse and Intra-Pulse Satellite Motion in Zero Doppler SAR Processing

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  - Several studies showed that pixel location accuracy at centimeter level is attainable.

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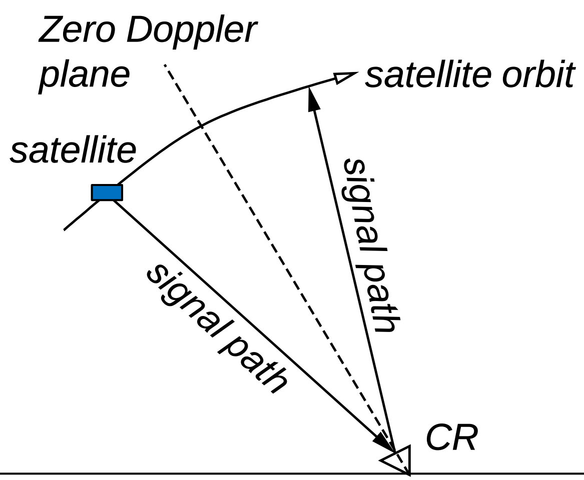
  - Where is the adequate place in processing chain to correct for them.
  - What is the attainable gain in location accuracy.
    - (based on Sentinel-1 and TerraSAR-X examples)

Inter-Pulse and Intra-Pulse Satellite Motion

Inter-Pulse Motion	Intra-Pulse Motion	Intra-Pulse Motion	Inter-Pulse Motion
From pulse transmission to echo reception	During echo reception	During pulse duration	Increase of signal travel distance



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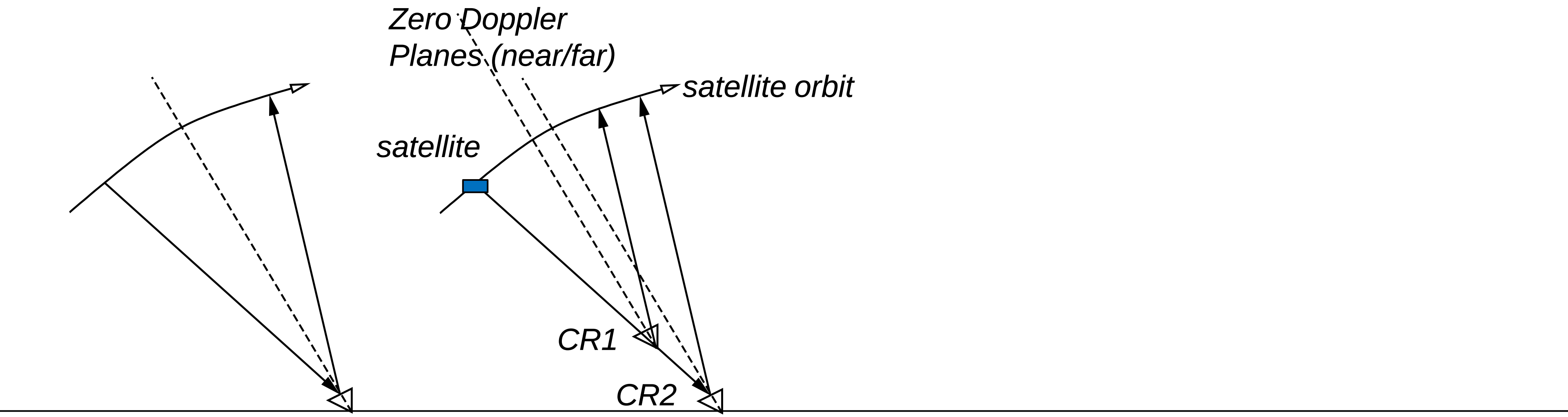

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Inter-Pulse Motion

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Intra-Pulse Motion

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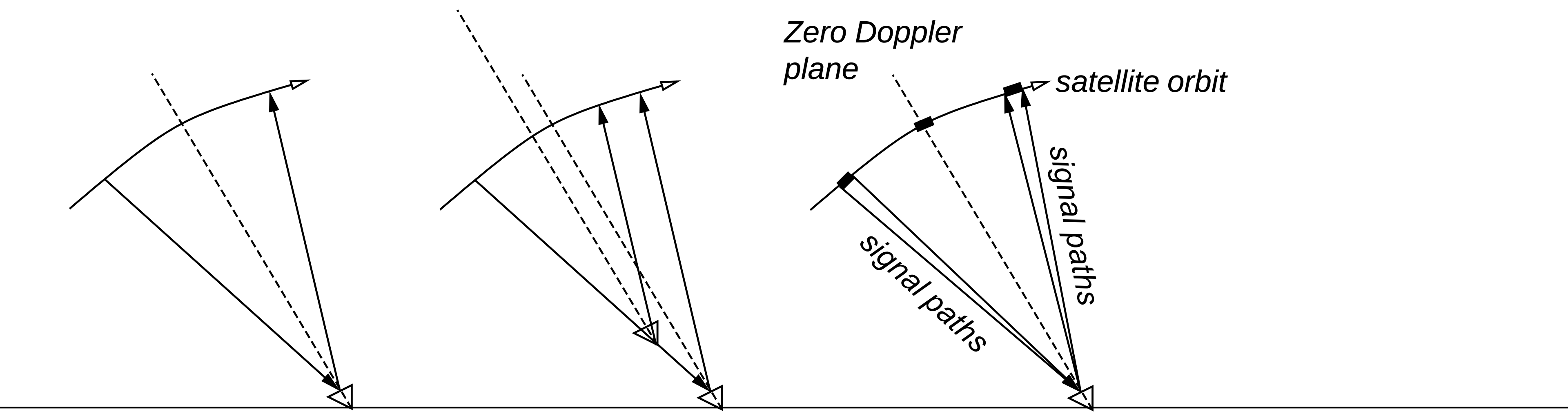

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Intra-Pulse Motion

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Inter-Pulse Motion

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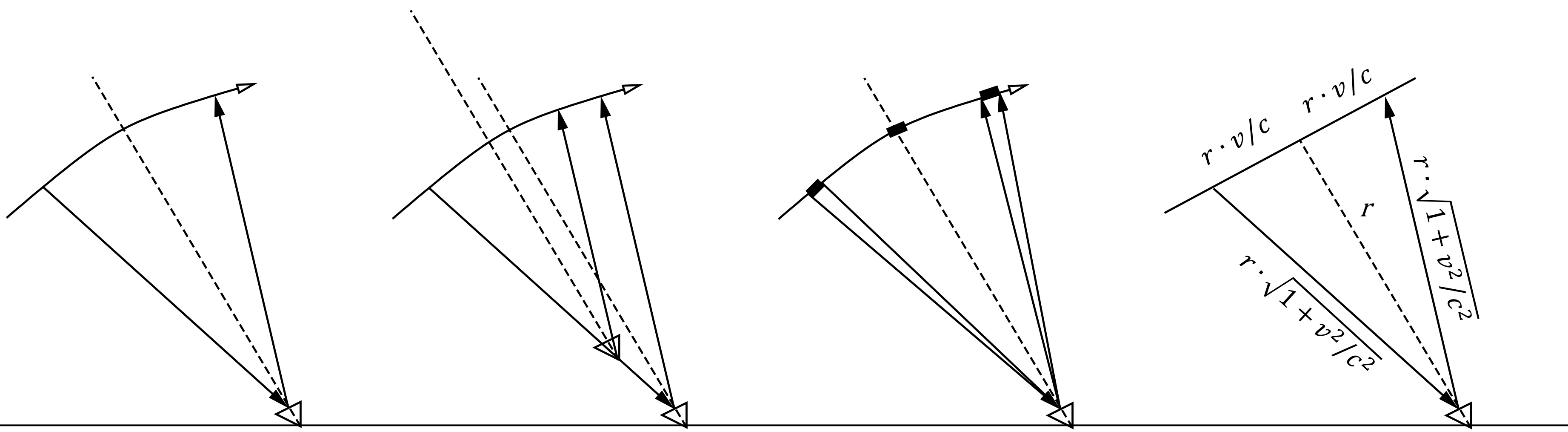

Amount of Effects in Case of Sentinel-1 and TerraSAR-X

Effect	Sentinel-1 azimuth	Sentinel-1 range	TerraSAR-X azimuth	TerraSAR-X range
Motion from pulse trans-mission to echo reception	(30 – 40 m)	–	(30 – 40 m)	–
Motion during echo reception	0.6 – 5.2 m	–	(0.04 – 3.8 m)	–
Motion during pulse duration	0.2 – 0.45 m	0.00 – 0.75 m*	(0.2 – 0.45 m)	(0.00 – 0.01 m)*
Increase of signal travel distance	–	0.15 – 0.25 mm	–	(0.15 – 0.25 mm)

Embraced values mean that the respective effect is already considered in SAR processor (*operational* IPF or TMSP).

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Motion from pulse transmission to echo reception
is considered by both SAR processor (IPF and TMSP).

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Motion during echo reception is consider by TMSP only.

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(* = secondary effect in range)

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Increase of signal travel distance is considered by TMSP (Spin-off from bistatic TanDEM mission).

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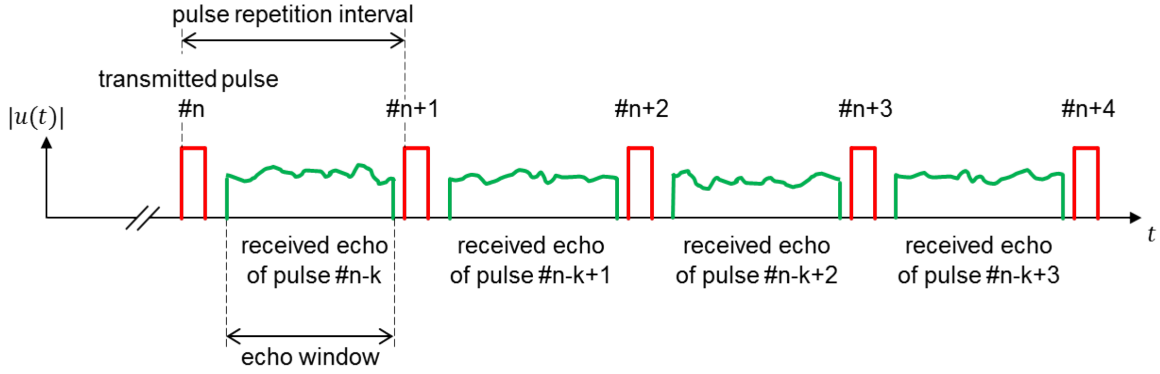
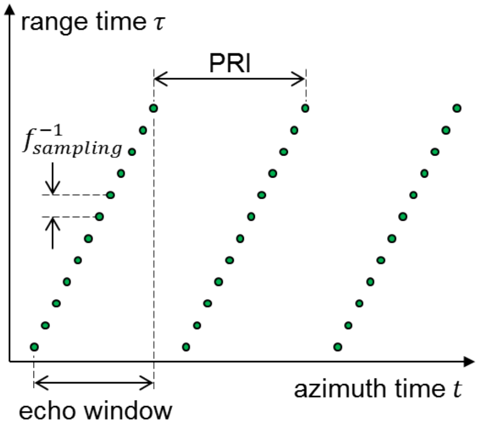
Increase of signal travel distance	**This effect is negligible so far!**			

Consequences of Satellite Motion on Raw Data

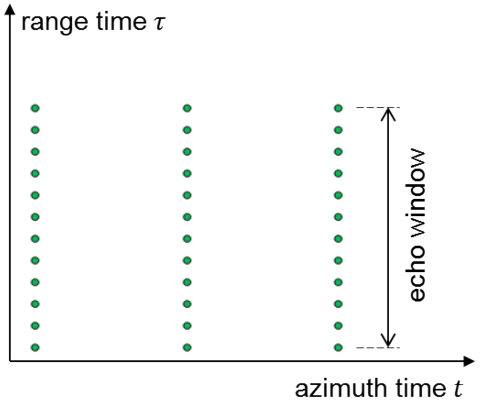
Contiguous echo data stream



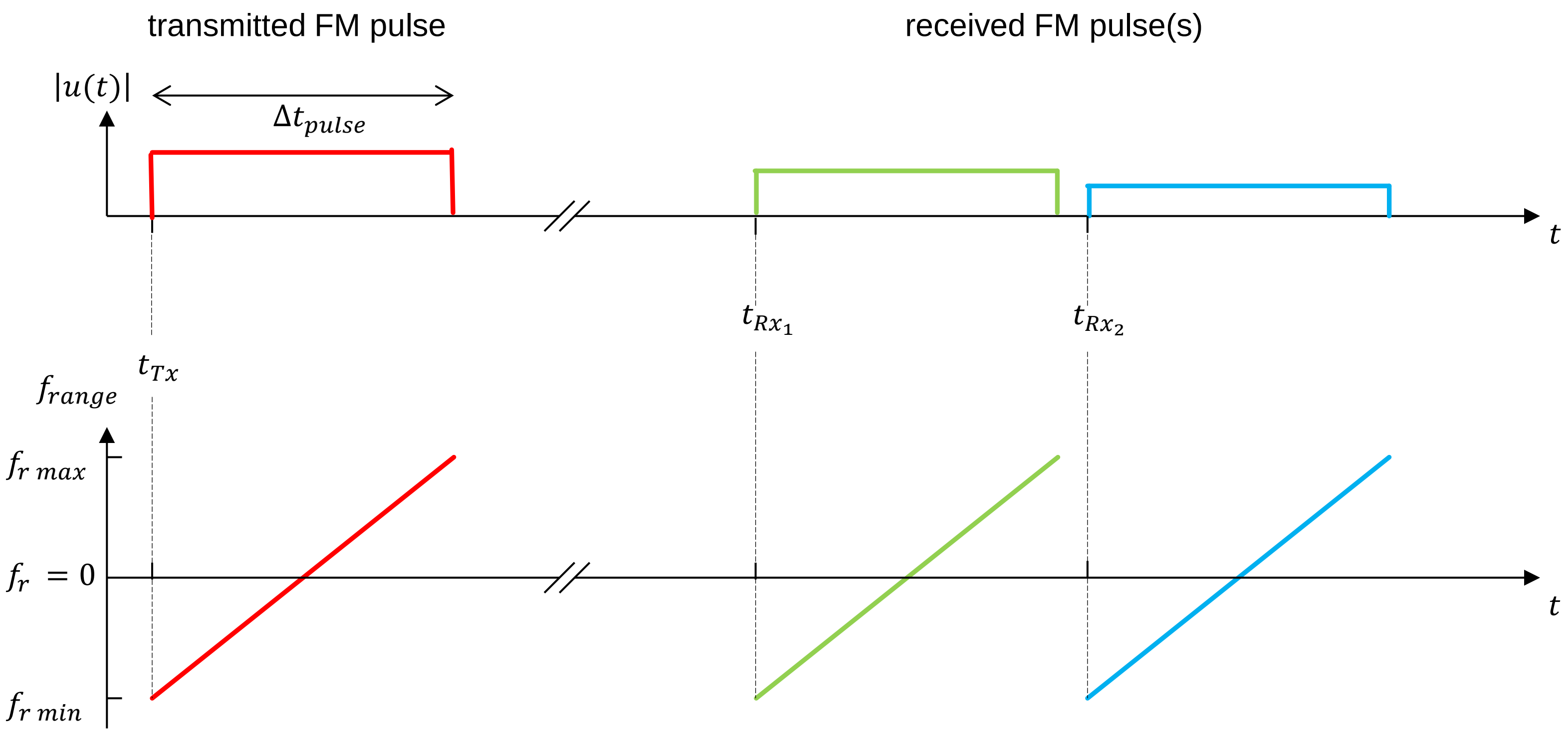
True timing of 2-D echo sample matrix



Timing, assumed by Stop-Go-Approximation

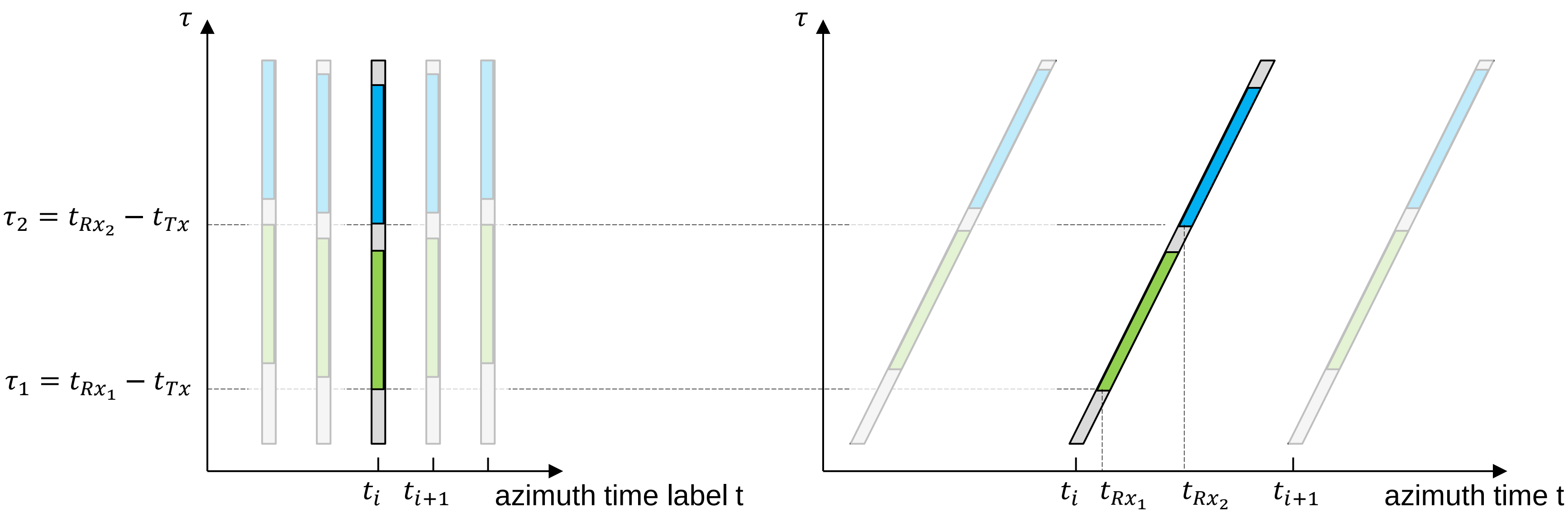


A pulse transmitted at t_{Tx} , scattered back from a ground target with a signal round trip time $\tau_{delay} = t_{Rx} - t_{Tx}$ is received at azimuth time t_{Rx}



SAR raw data matrix with
stop & go azimuth time labels

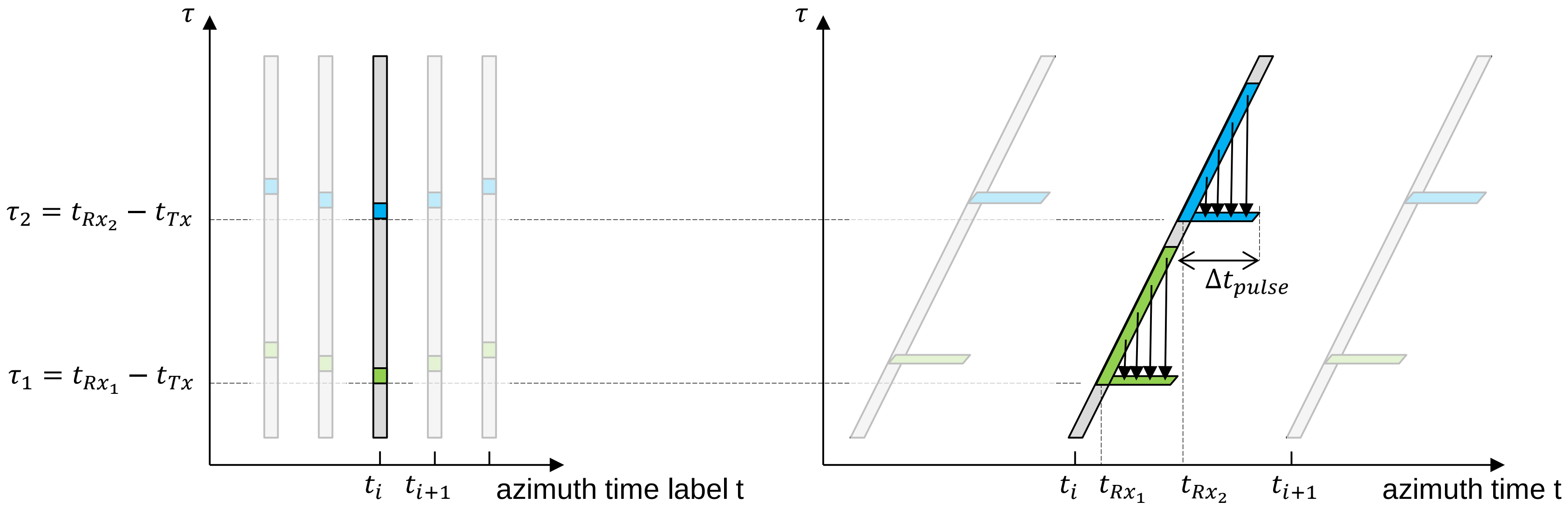
true azimuth timing of
SAR raw data matrix



Pulse Compression

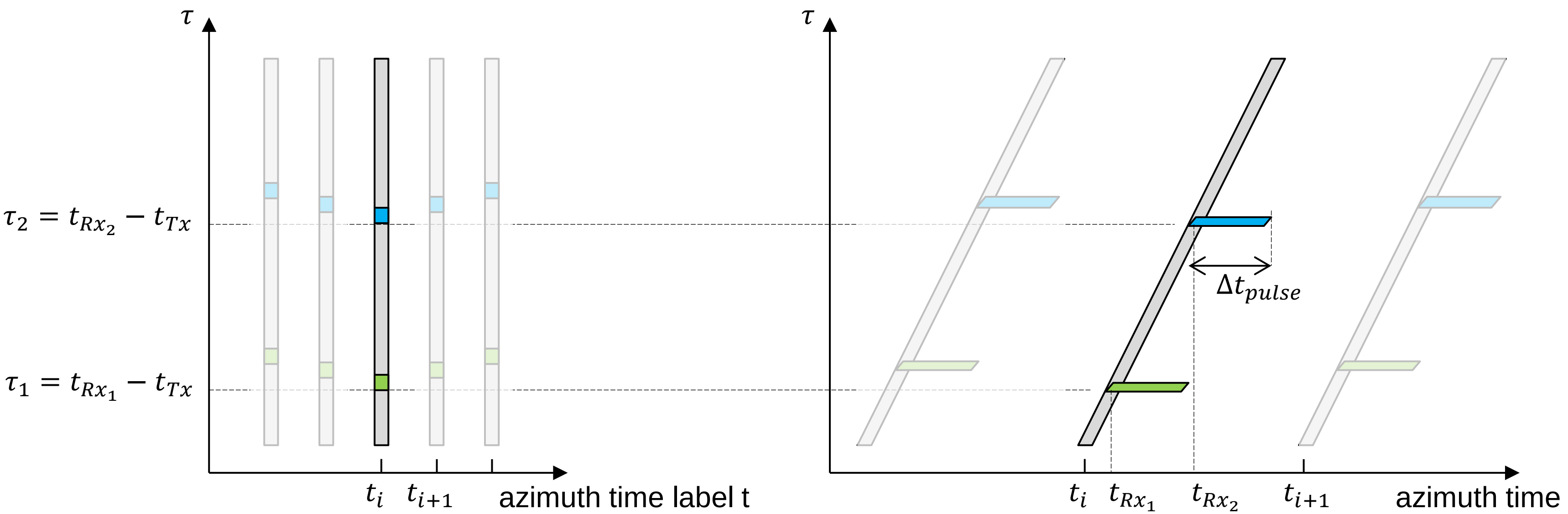
SAR raw data matrix with
stop & go azimuth time labels

true azimuth timing of
SAR raw data matrix



SAR raw data matrix after pulse compression with stop & go azimuth time labels

true azimuth timing of SAR raw data matrix after pulse compression



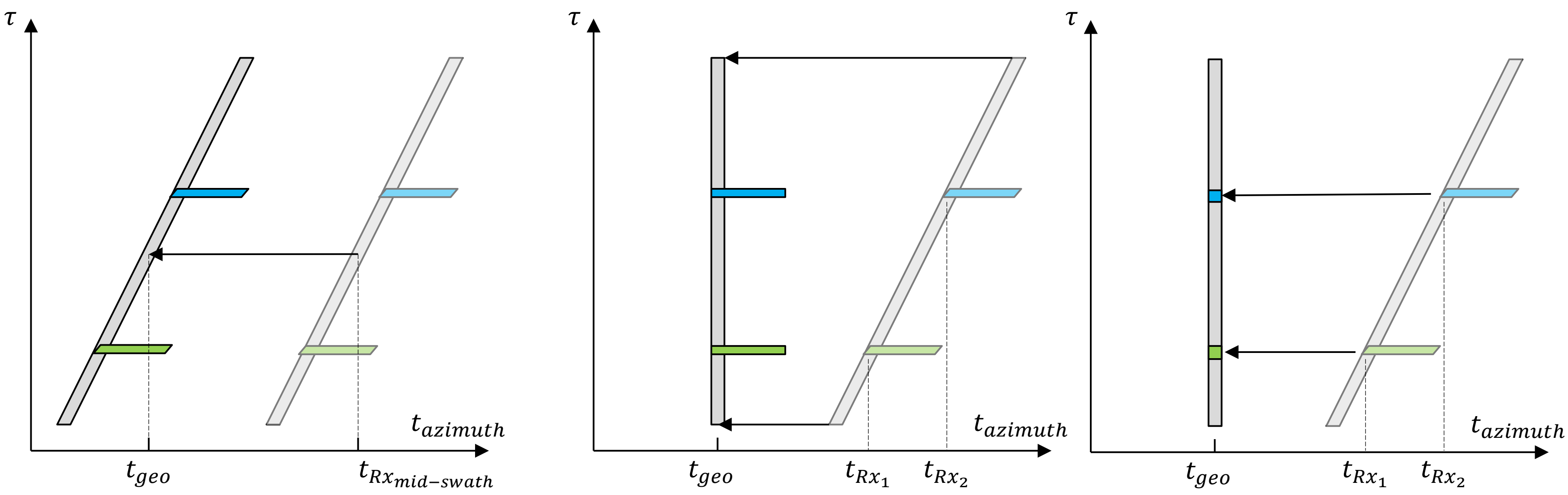
$\Rightarrow$ without correction of intra pulse motion range compressed data is smeared out in azimuth by the pulse duration Δt_{pulse}

Levels of Stop & Go Correction

Sentinel 1:
Partial stop & go correction:
- Inter pulse motion @ mid swath

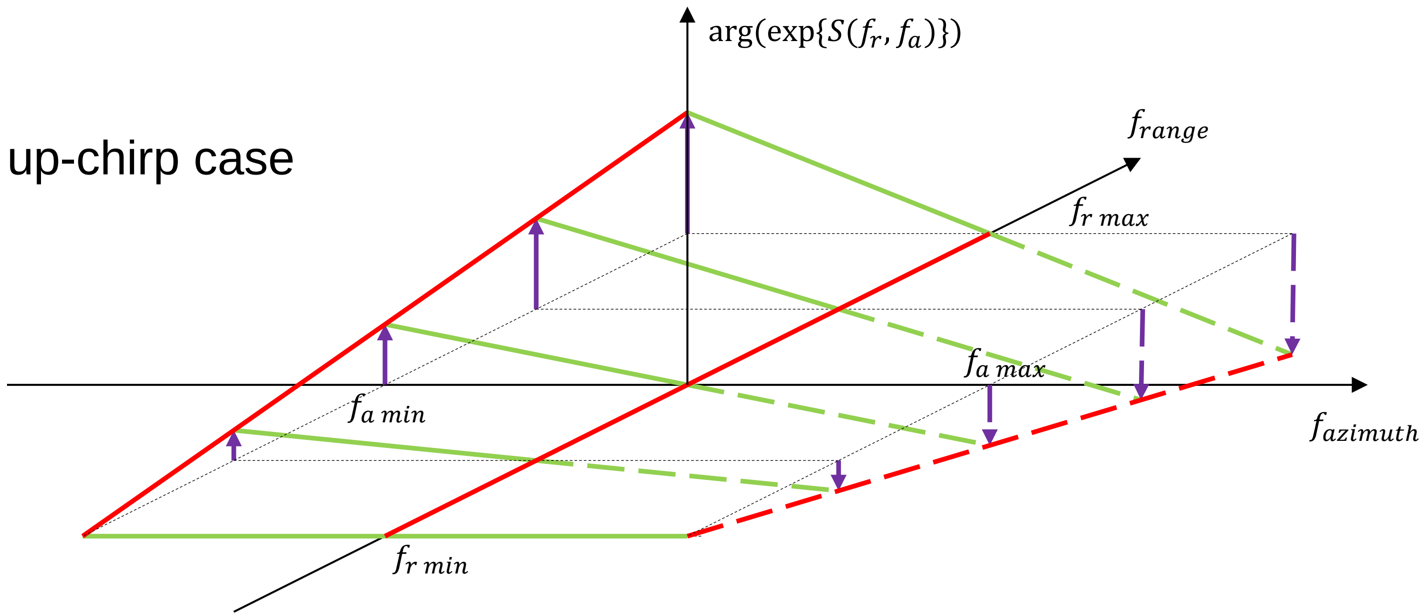
Partial stop & go correction:
- Inter pulse motion

TerraSAR-X:
Complete stop & go correction:
- Inter pulse motion
- Intra pulse motion



t_{geo} defines the time instant where the line of sight – satellite to target vector – is perpendicular to the flight trajectory and the zero-Doppler condition is fulfilled in a geometrical sense

Spectral Phase Slopes caused by Intra Pulse Motion



- f_{range} -dependent azimuth time offsets cause **spectral azimuth phase ramps** (green)
- **Spectral azimuth phase ramps** cause **spectral range phase ramps** (red)
- **Spectral range phase ramps** cause $f_{azimuth}$-dependent range time offsets

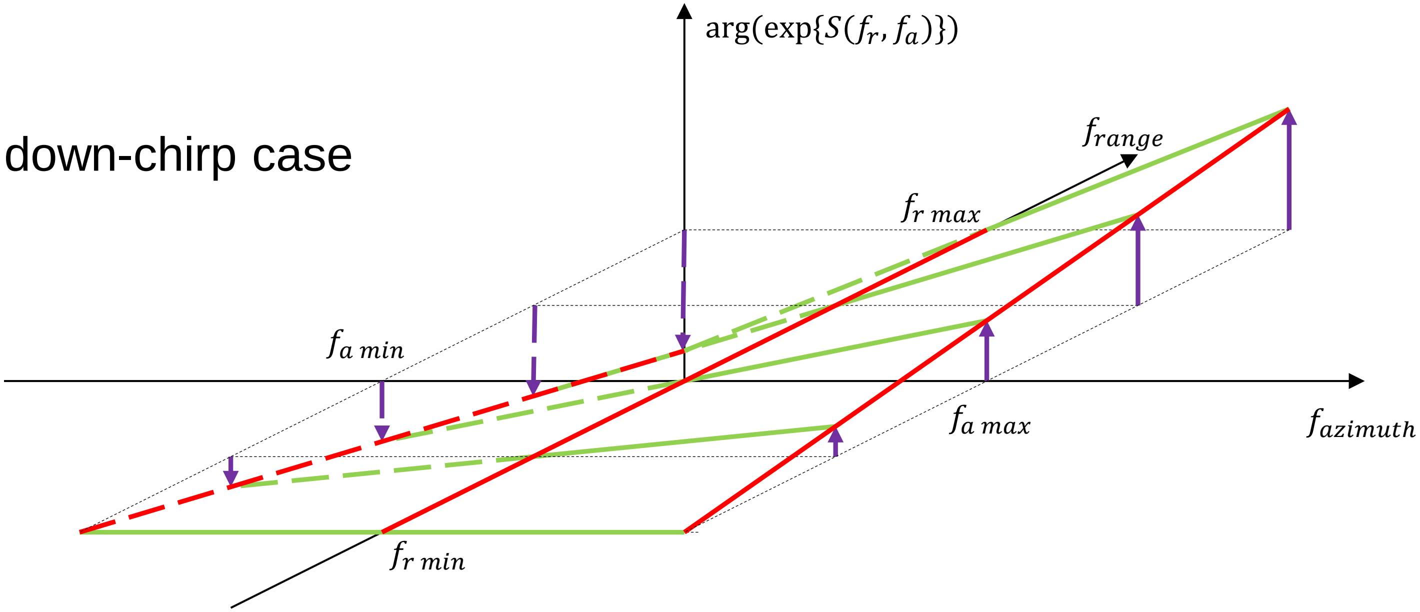
⇒ Stripmap Mode:

negative & positive spectral phase slopes sum up to defocusing (dm-level) but do not cause residual time offsets.

⇒ TOPS Mode: defocusing + DopCen-dependent range time offsets

Spectral Phase Slopes caused by Intra Pulse Motion

down-chirp case



Correction for Satellite Motion Effects

- Inter-pulse motion from pulse transmission to echo reception (approximately):

$$\boldsymbol{t \rightarrow t - \tau_{\mathrm{ref}}/2}$$

Already done in SAR processor.

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based on theoretical considerations

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opposite sign of correction in case of Sentinel-1 data (to be clarified)

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- Inter-pulse motion: Increase of signal travel distance:

$$\boldsymbol{\tau \rightarrow \tau \cdot \sqrt{1 - {v_{\mathrm{sat}}}^2/c^2}}$$

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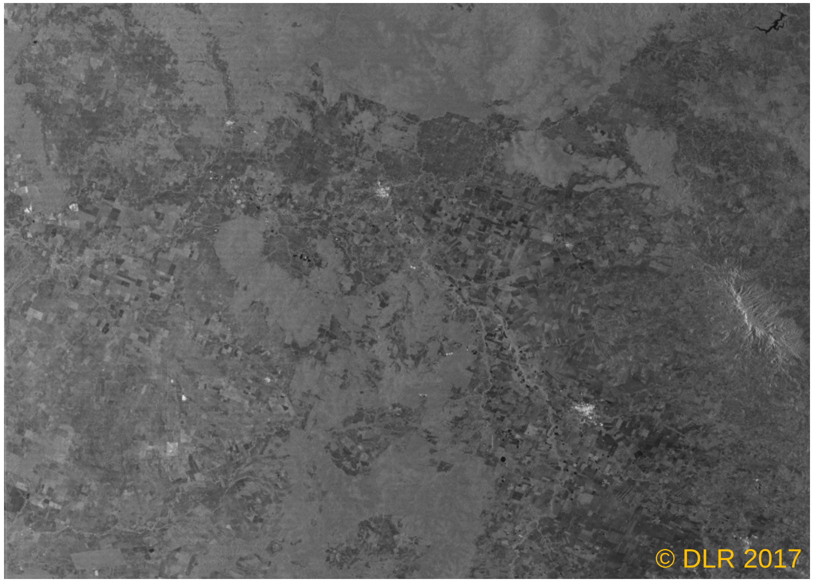
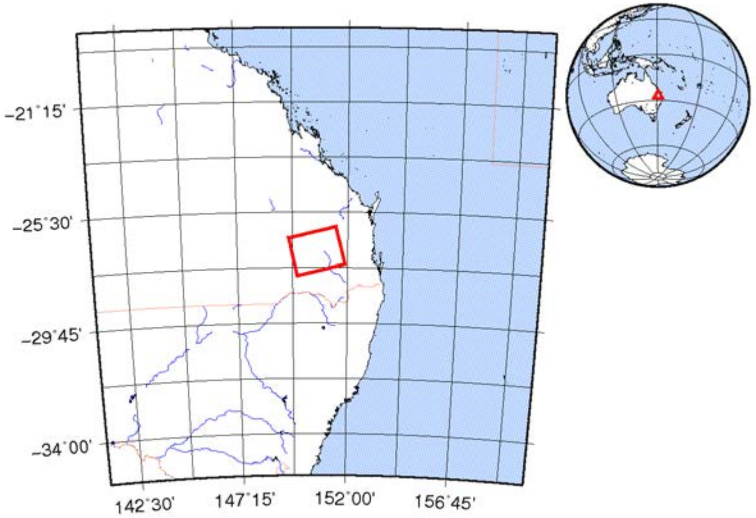
Surat Basin Test Site

- Located at **Surat Basin, Queensland, Australia**
- Operated by **Geosciene Australia** (GA)
- **40 CRs** with known reference coordinates from on-site survey (by GA)

- Regularly imaged by **Sentinel-1** in **IW** mode
- Imaged by **TerraSAR-X** in **SM, SC** and **Wide SC** mode



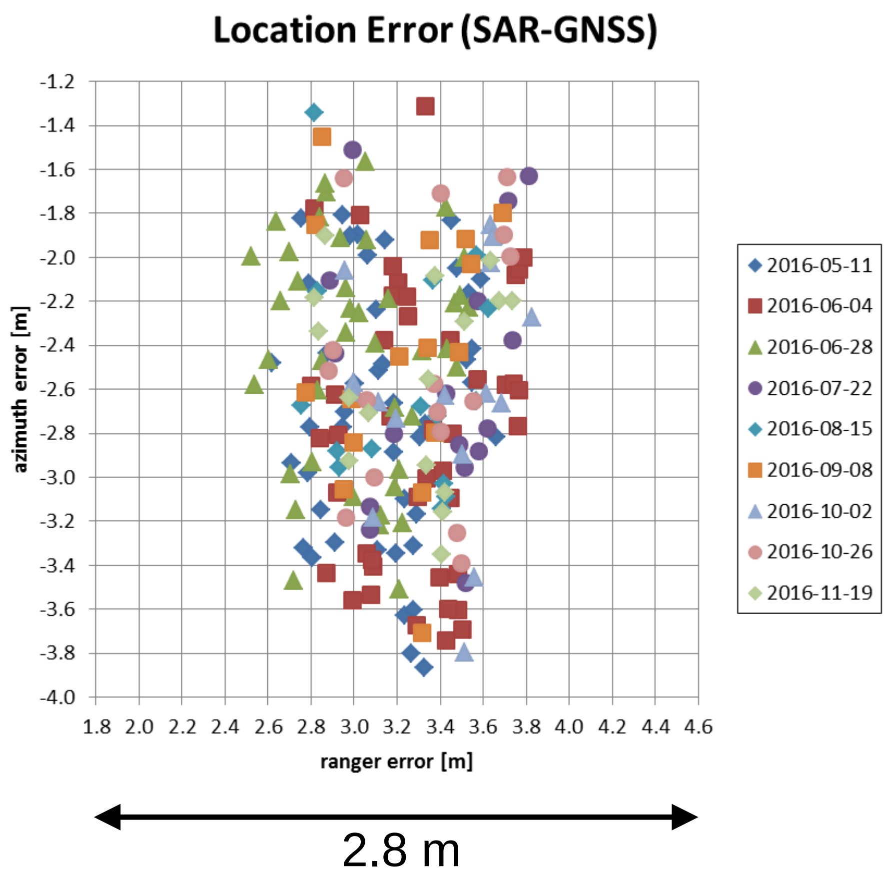
- **See also (at CEOS Workshop 2017):**
  - **Medhavy Thankappan et al.:** *"Calibration of Sentinel-1 and TerraSAR-X time-series SAR data over the Queensland Corner Reflector Array, Australia"*
  - **Christoph Gisinger et al.:** *"The limits of spaceborne SAR geolocation: Can we attain the 1 cm level?"*



Localization Accuracy of Sentinel-1 IW Mode

- Corrected:
  - ~~Signal propagation delays~~
  - ~~Solid earth tides~~
  - **Inter-pulse motion (by IPF)**
  - ~~Intra-pulse motion:~~
    - ~~Azimuth effect~~
    - ~~Range effect~~

- Location Error (SAR-GNSS):
  - Azimuth: -260 ± 57 cm
  - Range: +322 ± 31 cm



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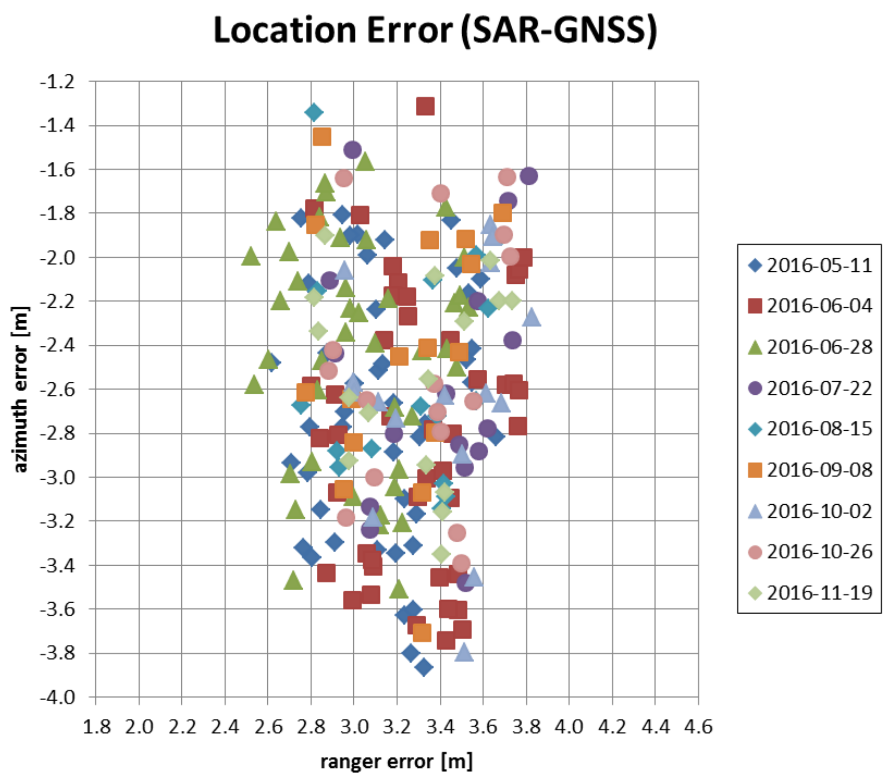

+1.8 m ⟷ +4.6 m

2.8 m

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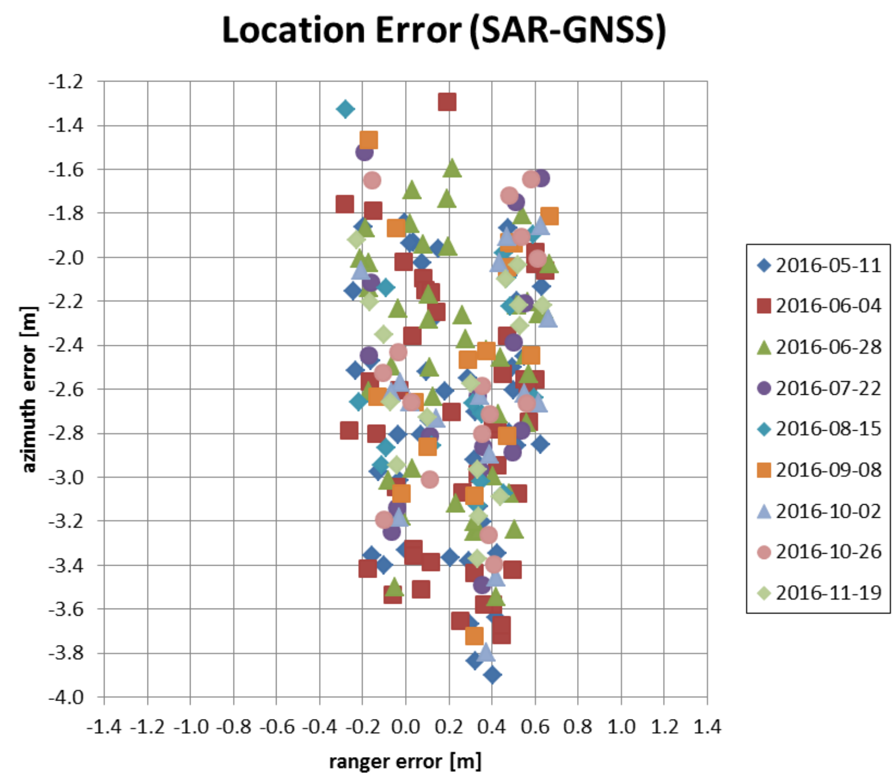
    - ~~Range effect~~

- Location Error (SAR-GNSS):
  - Azimuth: -261 ± 57 cm
  - Range: **<u>+24.0</u>** ± **26.8** cm

- Range bias almost removed
- Range standard deviation lowered by about 4 cm



-1.4 m ← 2.8 m → +1.4 m

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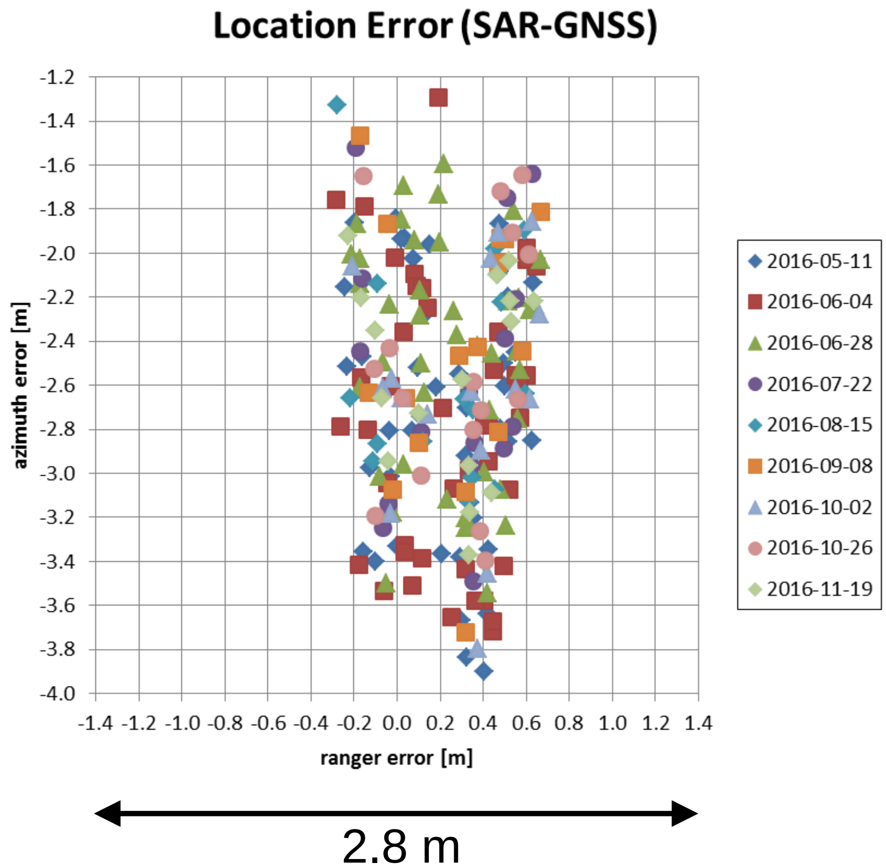

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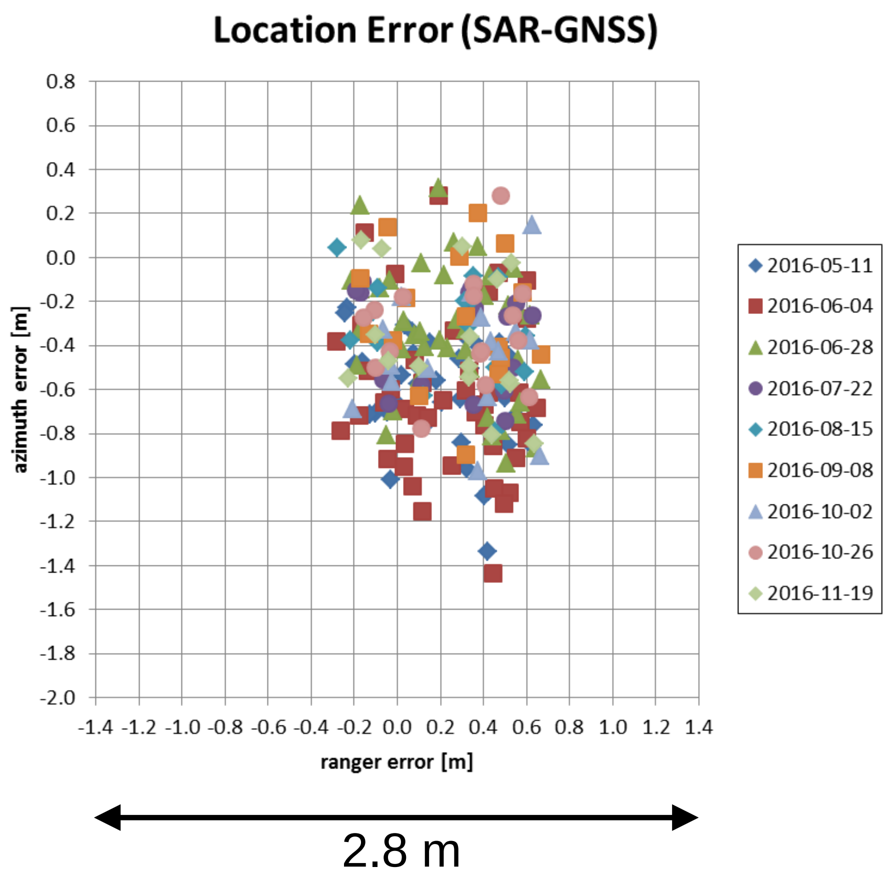
- Location Error (SAR-GNSS):
  - Azimuth: **-46** ± **31** cm
  - Range: +24.0 ± 26.8 cm

- Most of azimuth bias removed
- Azimuth standard deviation lowered by 26 cm



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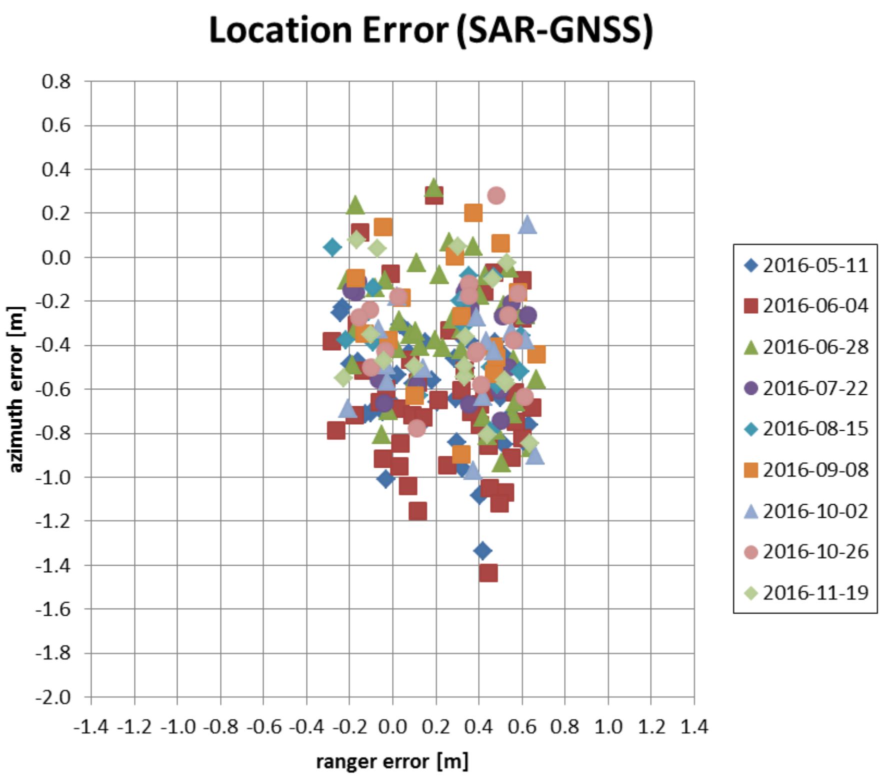

2.8 m

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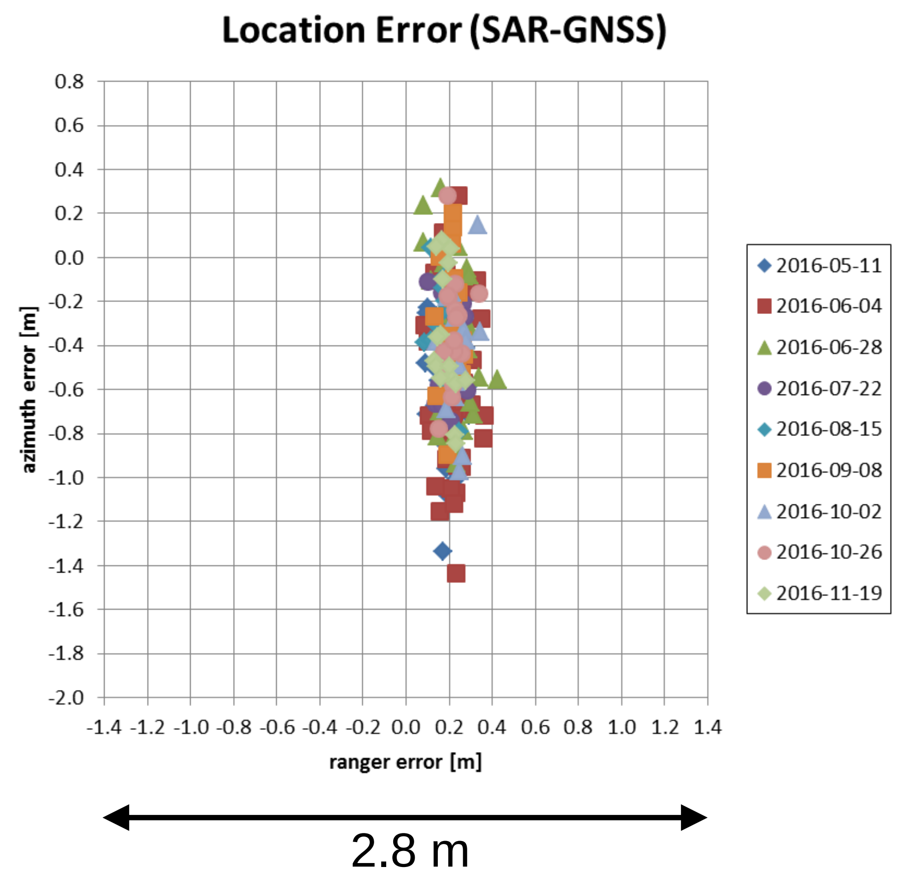
    - **Range effect**

- Location Error (SAR-GNSS):
  - Azimuth: -46 ± 31 cm
  - Range: **+20.9** ± <u>**5.7**</u> cm

- Range bias lowered by about 3 cm
- Range standard deviation drastically lowered (almost by factor 5).



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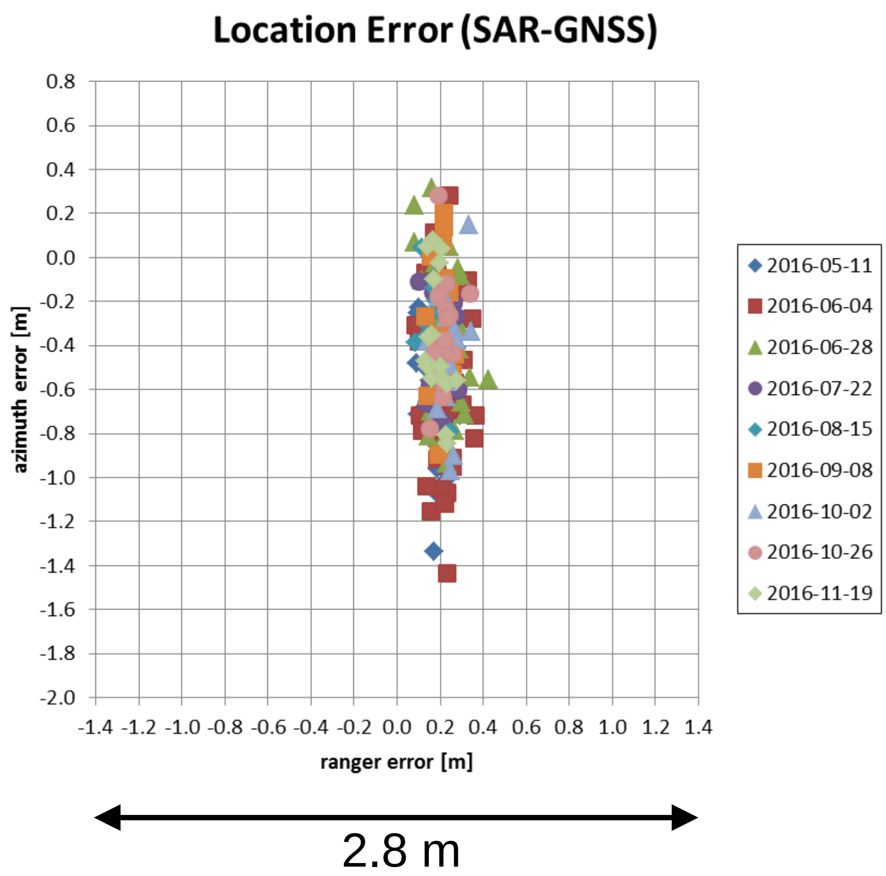
- Recommendation:
  - Biases shall be corrected by instrument recalibration



Localization Accuracy of TerraSAR-X Wide ScanSAR Mode

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  - Solid earth tides
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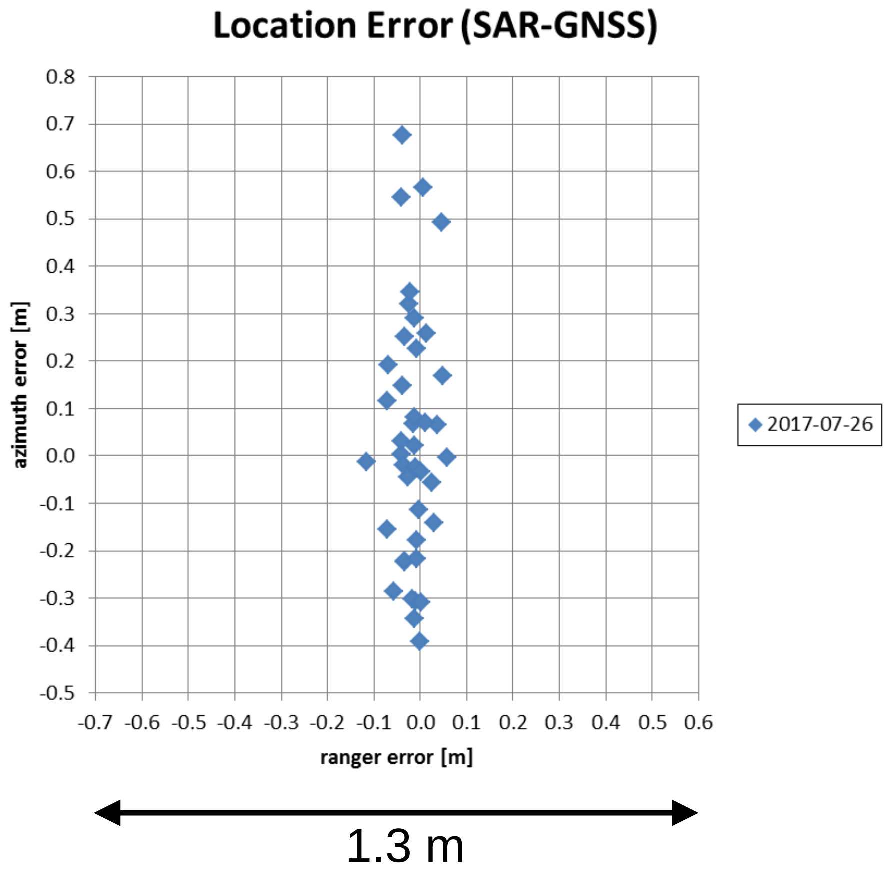
  - **Intra-pulse motion:**
    - **Azimuth effect (by TMSP)**
    - **Range effect (by TMSP)**

- Location Error (SAR-GNSS):
  - Azimuth: +3.8 ± 26 cm
  - Range: -1.6 ± 3.5 cm



Localization Accuracy of TerraSAR-X ScanSAR Mode (Eastern Part of Surat Basin)

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  - Intra-pulse motion:
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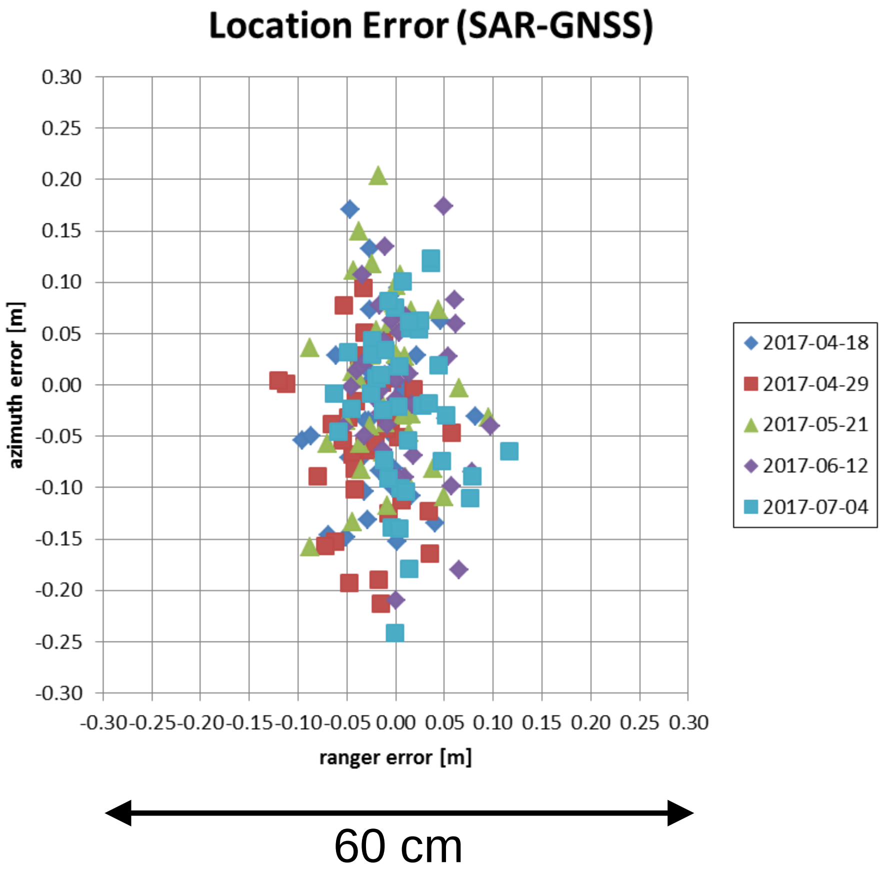
    - Range effect (by TMSP)

- Location Error (SAR-GNSS):
  - Azimuth: -2.1 ± 8.0 cm
  - Range: -0.8 ± 3.8 cm

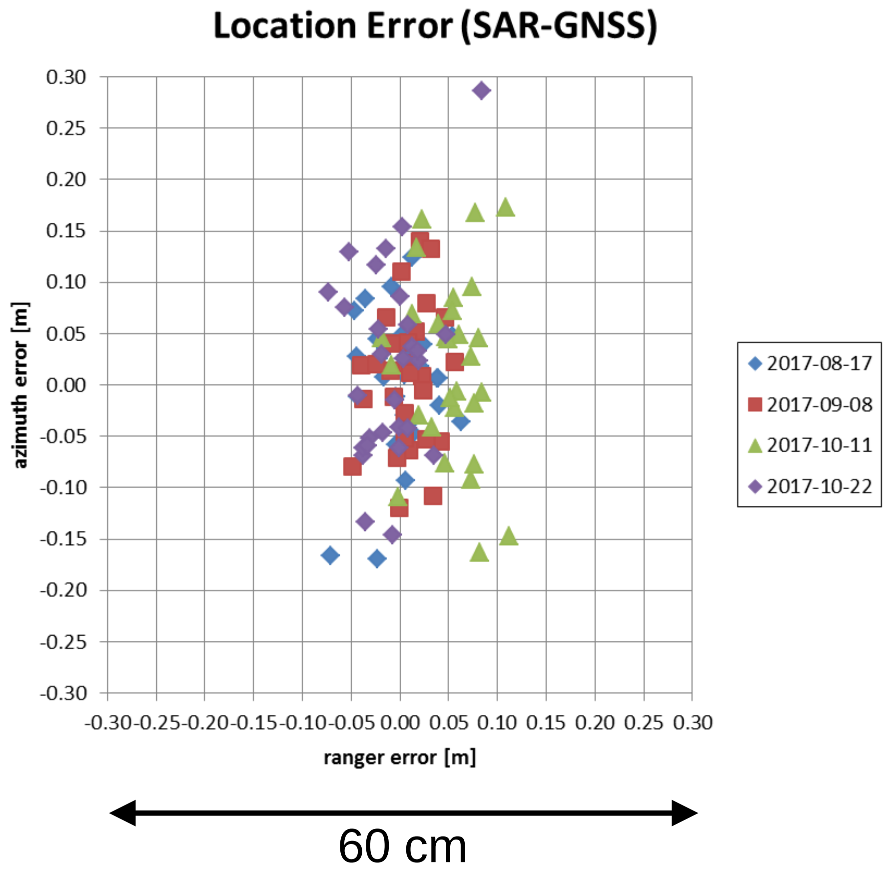


DLR

Localization Accuracy of TerraSAR-X ScanSAR Mode (Western Part of Surat Basin)

- Corrected:
    - Signal propagation delays
    - Solid earth tides
    - Inter-pulse motion (by TMSP)
    - Intra-pulse motion:
        - Azimuth effect (by TMSP)
        - Range effect (by TMSP)

- Location Error (SAR-GNSS):
    - Azimuth: +1.1 ± 8.0 cm
    - Range: +1.2 ± 3.9 cm



Conclusions

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DLR

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- Improvements of inter-pulse and intra-pulse motion corrections are demonstrated based on example datatakes from the Sentinel-1 mission.


Thank You for Your Attention!
Surat Basin seen by TDX-1: © DLR 2017

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